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Original Article

Effect of austempering conditions on the microstructure and mechanical properties of AISI 4340 and AISI 4140 steels

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ABSTRACT

AISI 4340 and AISI 4140 are normally used for different structural applications in quenched and tempered state due to their high strength, high abrasion and fatigue resistance but they lack toughness. Presence of dual phase microstructure such as ferrite-bainite and ferrite-martensite in steels have been reported to improve toughness but at the cost of strength. It is believed that development of bainite-martensite dual phase microstructure may help in obtaining better combination of mechanical properties. In this research work, development of bainite-martensite dual phase microstructure has been carried out at different austempering temperatures and times to study microstructure evolution and its effect on mechanical properties. Microstructural characterization of samples was carried out by scanning electron microscope (SEM) whereas mechanical characterization was done by performing hardness and impact testing. Development of dual phase bainite-martensite microstructure has shown to impart better combination of strength and toughness. In comparison with AISI 4140 steel, AISI 4340 provided better combination of hardness and toughness in the austempered state. It has been observed that decrease in the austempering temperature helped in obtaining better combination of hardness and impact strength in both grades of steels due to formation of lower bainite martensite dual phase microstructure at lower temperature.

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Table 1 – Chemical composition of alloys and their mechanical properties in non-heat treated conditions.

Grade	Composition of alloys (wt.%)[a]							Properties in non H.T condition	
	Ni	Cr	Mn	C	Mo	Si	Cu	Hardness (HV)	Toughness (Joules)
4340	1.61	0.88	0.6	0.42	0.29	0.18	0.03	335	22
4140	0.03	1.00	0.59	0.43	0.18	0.27	0.02	235.16	8

[a] Amount of S and P less than 0.001 and 0.010 respectively.

1. Introduction

Steel is generally used for majority of structural applications because of its low cost and possibility of obtaining wide range of mechanical properties through alloying addition, mechanical working or by microstructure manipulation [1]. Development of martensitic structure in steels for example provides high tensile strength and hardness but at the cost of toughness and ductility [2–5]. Development of equilibrium microstructure renders better toughness and ductility but with inferior mechanical strength. Strength and toughness are therefore considered as mutually exclusive properties. Development of bainitic microstructure especially lower bainite in steels has been reported to provide better combination of strength and toughness but it also causes loss in ductility at high volume fraction of bainite [6,7]. An optimum combination of mechanical properties can therefore be obtained in steels by development of dual phase microstructures [8–11]. Development of ferrite-martensite in steels, for example, have shown to impart much better combination of strength, toughness and ductility as compared to full martensitic structure due to strain hardening of ferrite in the vicinity of martensite [8,9]. Similarly, presence of softer ferrite in the vicinity of bainite in ferrite-bainite dual microstructure results in better strength, toughness and ductility as compared to full bainitic structure. Comparison of ferrite-bainite microstructure with ferrite-martensite microstructure shows that ferrite-bainite possesses high toughness and ductility than ferrite-martensite but their tensile strength is low. For applications where both strength and toughness are required these dual microstructures may not meet the requirements [8,9]. It is therefore, believed that combination of bainite and martensite may help in obtaining better combination of mechanical properties as bainite may induce toughness whereas martensite may enhance strength.

AISI 4340 and AISI 4140 are normally used in heat treated conditions for different structural applications such as landing gear in aircrafts, crankshafts in automotive, aircrafts frame, nuts, and steel roller [12–15] because they lack toughness in non-heat treated conditions [16–18]. Carbon content in these alloys ranges between 0.28 to 0.43% whereas silicon (Si), molybdenum (Mo) and chromium (Cr) are present in these alloys [18]. These elements not only contribute towards increase in hardenability but they also act as bainite stabilizers [19–22]. Chromium, for example, causes decrease in bainitic start temperature and increase in incubation time for bainitic transformation. Similarly silicon (Si) increases driving force for bainitic transformation and molybdenum suppresses pre bainitic reactions that hinder bainitic transformation [23–27]. Considering enhanced stability of bainite in AISI 4340 and AISI 4140, these alloys have been selected for studying development of dual phase bainite martensite microstructures and its effect on mechanical properties. Austempering is the most promising method to obtain dual phase bainite-martensite microstructure. In the present study, austempering of AISI 4340 and AISI 4140 steel has been carried out at different temperatures for different intervals of time in order to study microstructure evolution and its effect on mechanical properties.

2. Experimental setup

Chemical composition of studied alloys was determined with the help of optical emission spectroscopy. Time temperature transformation (TTT) curve, bainite start temperature (B_s) and martensite start temperature (M_s) was calculated for each alloy from its composition with the help of MAP_STEEL_MUCG46_90 software developed by Peet and Bhadesia [18,28]. Based on Bs and Ms, different austempering temperatures and times were selected to be able to study microstructure evolution as a function of time and temperature and their effect on mechanical properties. Samples were austenized at 900 °C for 30 min prior to the austempering treatment in sodium (50 wt. %) and potassium nitrates (50 wt. %) bath held at different temperature for different periods of time, followed by air cooling to the room temperature. Mechanical characterization of austempered samples was carried out with the help of hardness and impact tests. Samples for impact test were prepared according to the ASTM standard E23 and tested on pendulum impact tester. Hardness was determined with the help of micro Vickers hardness test in which 4900 kgf load was applied for 10 s. Samples were polished using standards metallographic procedures, etched with 2% nital, and observed on scanning electron microscope for microstructural characterization.

3. Results and discussions

Chemical composition and mechanical properties of selected alloys in their non-heat treated condition are listed in the Table 1.

Austenitization of the 4340 steel at 850 °C has been previously reported to result in incomplete dissolution of carbides and alloying elements [29,30]. In the present study, samples were therefore austenitized at 900 °C to ensure chemical homogeneity prior to austempering treatment. Prolong heating at high temperature may cause grain coarsening [30,31]. Samples were therefore austenitized at 900 °C for only 30 min and then quenched in salt baths maintained at different

Table 2 – Calculated Bs and Ms, and selected austempering conditions for the given grades of steels.

Grade	Calculated T (°C)		Austempering conditions	
	Bs	Ms	T (°C)	Time (mins)
4340	420	297	380, 340, 310	30, 60, 90
4140	492	322	452, 412, 372	30, 60, 90

austempering temperatures for different periods of time. Details of austempering conditions selected on the basis of calculated values of bainitic start (B_S) and martensitic (Ms) are provided in the Table 2.

3.1. AISI 4340

SEM micrographs of AISI 4340 austempered at 380 °C, 340 °C and 310 °C for 30 min, 60 min, and 90 min are shown in Fig. 1. Light phase in microstructures represent bainite and the dark phase indicate martensite whereas small dark blocks are of retained austenite. It can be observed from the micrographs that amount of retained austenite at a particular austenitizing temperature is highest in the sample austempered for 30 min and decreased with increase in soaking time. Volume fraction of martensite after 30 min of soaking was large as only small amount of austenite converted to bainite and most of remaining austenite has been converted to martensite on subsequent air cooling. Increase in the soaking time resulted in increase in the amount of bainitic transformation thereby resulting in decrease in the amount of martensitic transformation on air cooling. Therefore, microstructures after 60 min of austempering consisted of bainite as dominating phase along with relatively smaller amount of martensite and retained austenite. A small increase in the amount of bainite was observed by increase in the soaking time from 60 to 90 min which indicated majority of bainitic transformation was completed up to 60 min of austempering. However, amount of retained austenite kept on decreasing by increase in the soaking time. Austempering at 380 °C resulted in the formation of thick needles indicating presence of upper bainite whereas microstructural characterization of the samples austempered at 340 °C indicated the presence of both upper and lower bainite. Austempering at 310 °C caused precipitation of cementite inside the ferrite plates due to slow diffusion of carbon at 310 °C resulting in the formation of lower bainite in the microstructure. Amount of retained austenite has been observed to decrease with decrease in austempering temperature. This is due to the fact that chances for bainitic transformation increase with the decreasing temperature [1] resulting in the increased amount of bainite at the cost of retained austenite. Microstructures of the 4340 samples after different austempering conditions are shown in the Fig. 1.

Micro Vickers hardness and Charpy impact tests were performed in order to study the effect of microstructural evolution on the mechanical properties of 4340 steel. Mechanical characterization results of heat treated 4340 steel samples are shown in the Fig. 2. Hardness of samples, irrespective of the austempering temperature, was highest for the samples soaked for 30 min which initially decreased with the increase in the soaking time and then increased. Higher value of hardness was achieved in the samples soaked for 30 min as short austempering time allowed only small amount of bainitic transformation thereby causing supersaturation of carbon in austenite which induces a lot of lattice strain in the martensite formed as a result of subsequent air cooling. The resultant microstructure of the samples austempered for 30 min consists of small amount of bainite along with large amount of martensite and solute hardened retained austenite. The presence of these phases in microstructure results in high hardness of samples austempered for 30 min. Hardness of the samples decreased significantly by increase in the soaking time from 30 to 60 min. Increase in the soaking time resulted in more conversion of the austenite to the bainite during austempering thereby leaving less amount of austenite for martensitic transformation on subsequent air cooling. Increase in the amount of bainite in the microstructure also resulted in decrease in the lattice strains due to carbide precipitation and recovery of defects. These factors contribute to decrease in hardness of samples austempered for 60 min. As majority of the bainitic transformation was completed at about 60 min of austempering, further increase in the soaking time to 90 min caused small increase in the hardness which may be attributed to the increased conversion of retained austenite into martensite.

Effect of microstructural evolution on the impact toughness of the 4340 samples was evaluated by carrying out Charpy impact test. Variation of impact strength as a function of soaking time as well as austempering temperature has been shown in the Fig. 2. Impact strength of the samples austempered for 30 min was lowest due to large amount of the solute hardened retained austenite and martensite in the microstructure and lattice strains. Increase in the soaking time to 60 min caused increase in the impact strength due to more amount of bainite in the microstructure and reduced amount of lattice strains. As discussed earlier, majority of the bainitic transformation was completed in 60 min; further increasing the soaking time caused more conversion of retained austenite to the martensite which reduced toughness of the samples. Increase in the soaking time also causes precipitates coarsening which also contributed towards decrease in the impact strength.

Comparison of hardness and impact trends at different austempering temperature (380 °C, 340 °C and 310 °C) showed that both the impact strength and hardness of samples increases with decrease in temperature due to the formation of lower bainite at lower temperatures. Dual microstructure of lower bainite and martensite obtained by austempering at temperature close to Ms for intermediate interval of time provided better combination of hardness and toughness in AISI 4340 steel.

3.2. AISI 4140

SEM micrographs of AISI 4140 austempered at 452 °C, 412 °C and 372 °C for 30, 60, and 90 min has been shown in Fig. 3. Light phase in AISI 4140 micrographs represent bainite and dark phase indicate martensite whereas small dark blocks are of retained austenite. Microstructure evolution trends were the same as were observed during austempering of the 4340 steels. Samples austempered for 30 min contained large amount of martensite and retained austenite than the bainite. Increase in the soaking time to 60 min caused decrease in

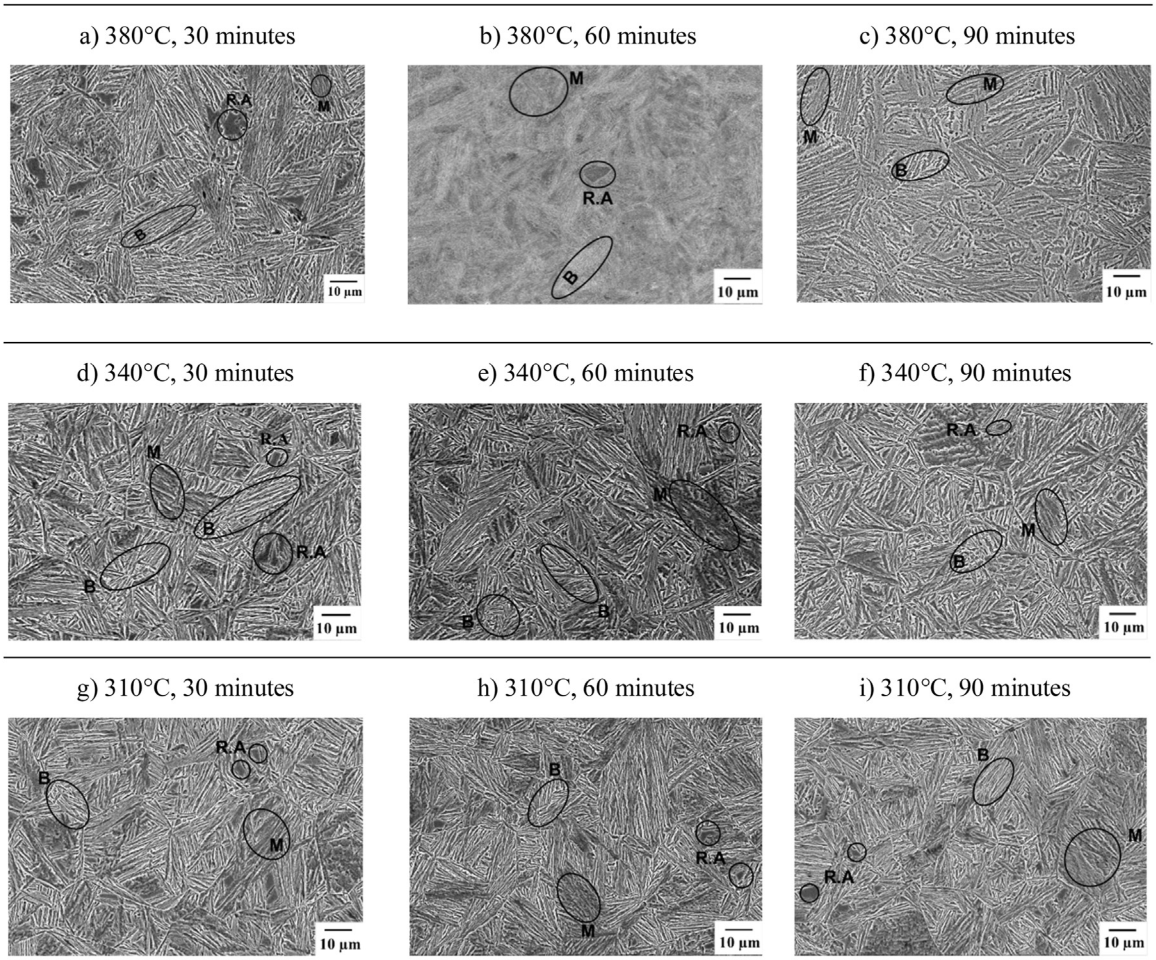

Fig. 1 – Microstructure evolution of AISI 4340 as a function of austempering temperature and time.

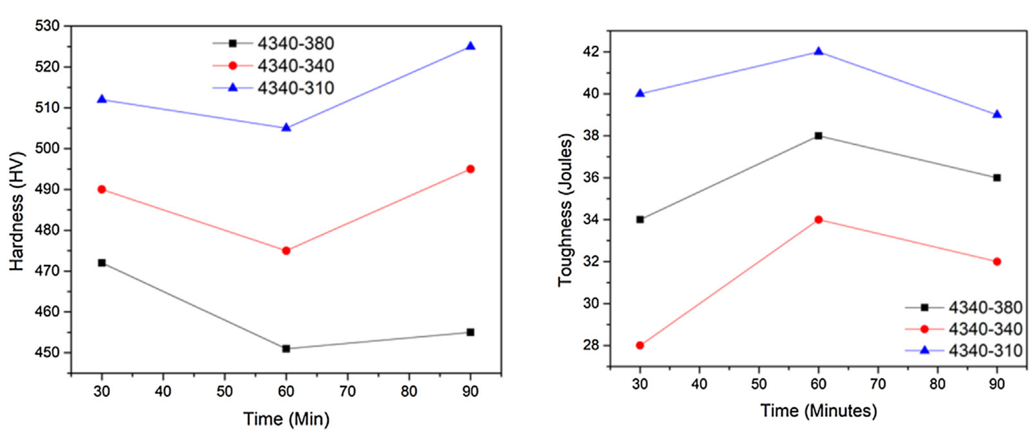

Fig. 2 – Variation of hardness and toughness of AISI 4340 as a function of austempering temperature and time.

the amount of retained austenite whereas amount of bainite increased. Further increase in the soaking time caused only a small increase in the amount of bainite indicating majority of the bainitic transformation was completed in 60 min of soaking time. Amount of retained austenite, on the other hand, decreased with the increase in the soaking time as it converted into martensite. Samples austempered for 90 min therefore contained more amount of martensite than the samples austempered for 60 min. Microstructural characterization of samples austempered at 452 °C revealed presence of thick bainite plates, indicating presence of upper bainite. Samples austempered at 412 °C indicated presence of upper as well as lower bainite whereas austempering at 372 °C resulted in the formation of lower bainite because relatively slow diffusion

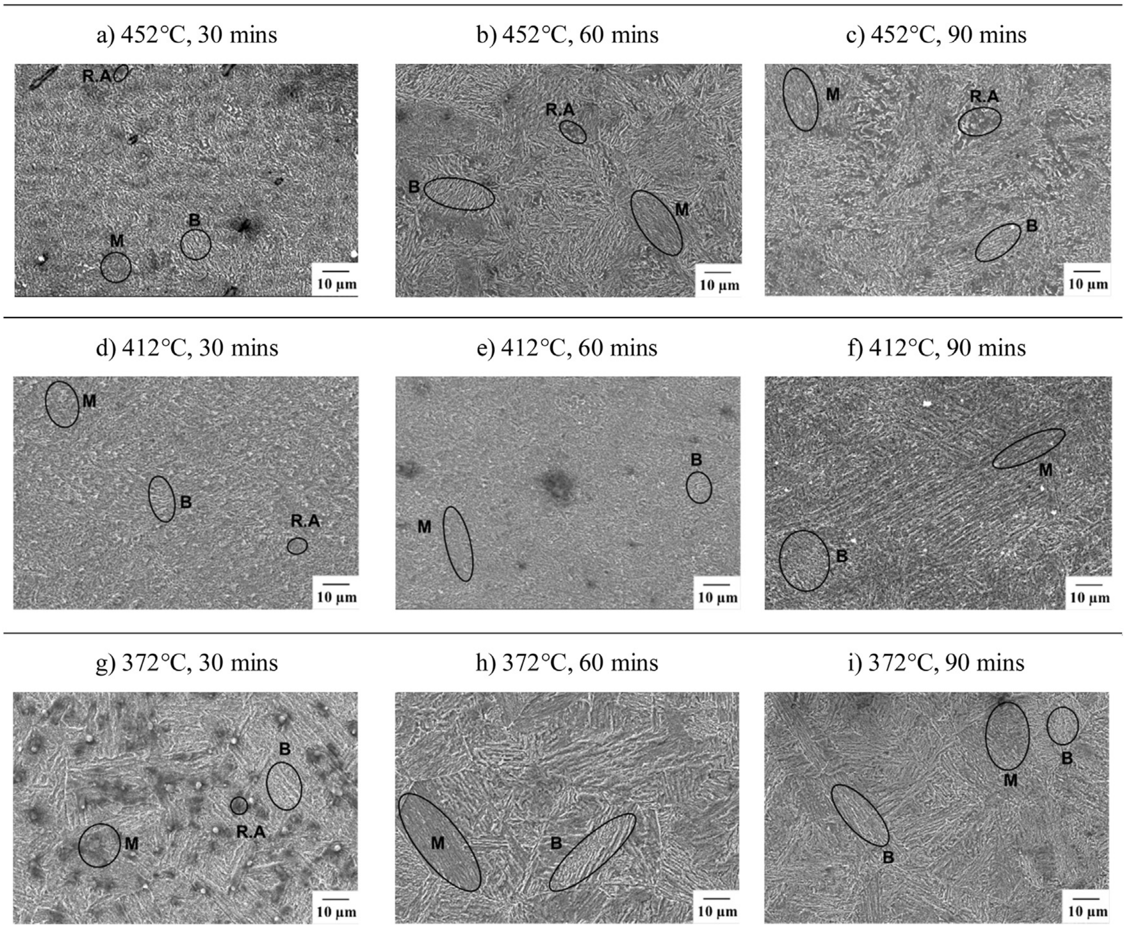

Fig. 3 – Microstructure evolution of AISI 4140 as a function of austempering temperature and time.

of carbon at this temperature caused cementite precipitation only within the ferrite plates.

Mechanical characterization results of the samples austempered at 452 °C, 412 °C and 372 °C for 30, 60, and 90 min are shown in the Fig. 4. At all austempering temperatures, hardness of samples has been initially observed to decrease with increase in the soaking time and then increase whereas opposite pattern was observed for the toughness. Values of hardness after 30 min of soaking were high due to large amount of martensite, solute hardened austenite and lattice strains in the microstructure. Presence of these phases in the microstructure contributes to high hardness of samples austempered for 30 min. However, increasing the soaking time to 60 min caused increase in the amount of bainite, decrease in hardness and increase in the toughness. As majority of the bainitic transformation was completed in 60 min, further increase in the soaking time to 90 min only caused slight increase in the amount of bainite. However, the amount of martensite increased significantly due to increased conversion of retained austenite to martensite. As a result, hardness of the samples increased whereas decrease in the toughness was evidenced.

Hardness vs. impact strength comparison of the given grades of steel as a function of austempering time and temperature is shown in the Fig. 5.

It can be seen from the Fig. 5 that austempering treatment has considerably increased the hardness as well as impact strength of studied steel grades. In addition, decrease in austempering temperature rendered better combination of hardness and impact strength. This trend has been found valid for AISI 4340 as well as for the AISI 4140 steel. High austempering temperatures resulted in the formation of upper bainite which imparted relatively poor combination of mechanical properties due to coarser microstructure. Increase in the hardness as well as impact strength by decrease in temperature has been attributed to the slow diffusion of carbon at lower temperatures which resulted in the formation of lower bainite. Lower austempering temperatures also contributed towards development of finer microstructure which resulted in better mechanical properties. Amount of bainitic transformation has been previously reported to increase by decrease in the temperature [1] which has also contributed towards increase in hardness as well as increase in the impact strength of the samples austempered at low temperatures. Intermediate soaking times at a given austempering temperature resulted in optimum combination of hardness and impact strength due to the presence of more amount of bainite and limited amount of martensite in the microstructure. Low and high soaking times resulted in formation of large amount of martensite, thereby increasing hardness at the

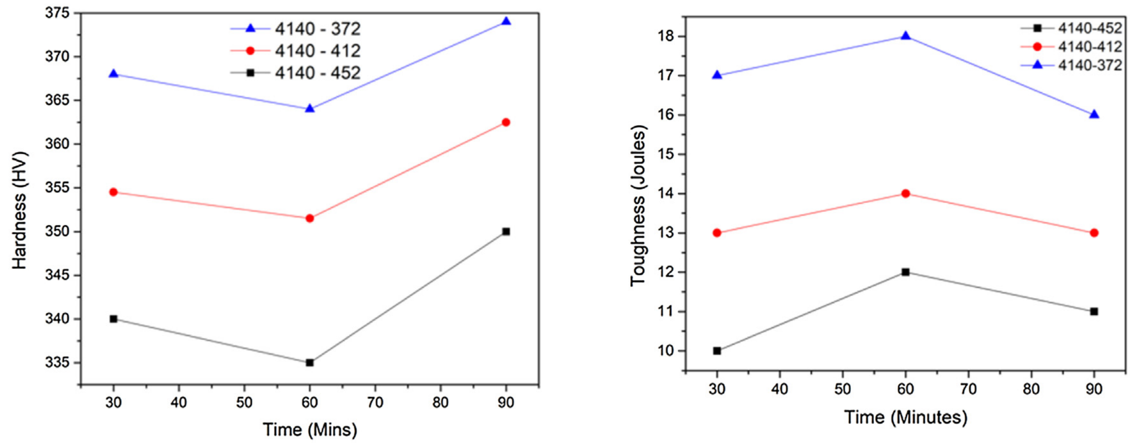

Fig. 4 – Variation of hardness and toughness of AISI 4140 as a function of austempering temperature and time.

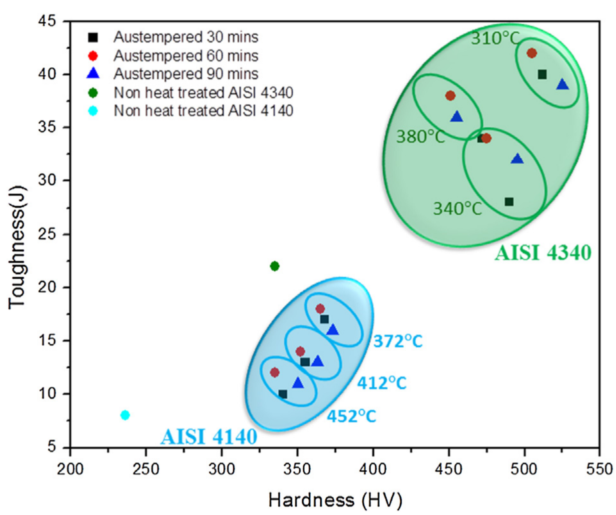

Fig. 5 – Hardness vs. toughness comparison of austempered AISI 4340 and austempered AISI 4140 steel.

cost of toughness. In comparison with the AISI 4140 steel, AISI 4340 has been showed to possess much better combination of hardness and impact strength in the austempered state. As indicated in the Table 1, carbon content is same in both steels; however, nickel is only present in AISI 4340 steel. Addition of nickel has been previously reported to adversely affect kinetics of bainitic transformation by hindering precipitation of carbides. However, it has also been reported to reduce the Bs as well as Ms temperatures which helped in obtaining much better combination of mechanical properties by permitting lower temperature austempering treatments. Low temperature austempered AISI 4340 steels containing dual phase bainite-martensite microstructure are therefore the more promising candidates for applications where high values of both hardness and toughness are required. Alloying additions and/or increasing the amount of elements that decrease B_S as well M_S of AISI 4340 is recommended. It will help in obtaining even better combination of mechanical properties due to the presence of large amount of finer lower bainite in the microstructure.

4. Conclusion

1. Effect of austempering temperatures and soaking times on the microstructure development and mechanical properties of AISI 4340 and AISI 4140 steels has been evaluated.
2. Development of bainite-martensite dual phase microstructure helped in obtaining better combination of mechanical properties.
3. Decrease in the austempering temperature has been found to increase the values of both hardness as well as toughness due to the formation of large amount of fine grained lower bainite along with the martensite. It has therefore been recommended to develop alloys with lower Bs and Ms so that even lower temperature austempering treatments may be carried out to obtain even better combination of mechanical properties.
4. At a given austempering temperature, hardness of the alloys austempered for 30 min is more due to relatively larger amount of martensite whereas samples austempered for 60 min showed better toughness due to large amount of bainite in the microstructure.
5. In comparison with AISI 4140, AISI 4340 has shown better combination of mechanical properties in austempered state and should be therefore preferred for more demanding structural applications.

Conflicts of interest

The authors declare no conflicts of interest.

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